

# A Blue Straggler Binary with Three Progenitors in the Core of a Globular Cluster?<sup>1</sup>

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## ABSTRACT

We show that the X-ray source W31 in the core of the globular cluster 47 Tucanae is physically associated with the bright blue straggler BSS-7. The two sources are astrometrically matched to  $0.061''$ , with a chance coincidence probability of less than 1%. We then analyse optical time-series photometry obtained with the *Hubble Space Telescope* (HST) and find that BSS-7 displays a 1.56 day periodic signal in the I band. We also construct a broad-band (far-ultraviolet through far-red) spectral energy distribution for BSS-7 and fit this with single and binary models. The binary model is a better fit to the data, and we derive the corresponding stellar parameters.

All of our findings are consistent with BSS-7 being a detached binary consisting of a blue straggler primary with an X-ray-active, upper-main-sequence companion. The formation of such a system would necessarily involve at least three stars, which is consistent with recent N-body models in which blue stragglers often form via multiple encounters that can involve both single and binary stars. However, we cannot yet entirely rule out the possibility that BSS-7 descended directly from a binary system via mass transfer. The system parameters needed to distinguish definitively between these scenarios may be obtainable from time-resolved spectroscopy.

*Subject headings:* blue stragglers — globular clusters: individual (47 Tucanae)

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## 1. Introduction

Blue straggler stars (BSSs) are objects with roughly main-sequence colors and magnitudes that are significantly bluer and brighter than the main-sequence turn-off (MSTO) point appropriate to their environment. Their name derives from the fact that they should have evolved off the MS long ago, i.e. they appear to “straggle” on the evolutionary path taken by ordinary stars. Since the MSTO is a function of age, BSSs are most easily detected in co-eval stellar populations, such as star clusters. Globular clusters (GCs) provide a particularly interesting setting for studying BSSs, since the ultra-high stellar densities found in the cores of GCs (up to one million stars per cubic parsec) open up new channels for BSS formation via dynamical encounters between cluster members (e.g. Hut et al. 1992).

BSS have been found in essentially all galactic globular clusters (GCs) (e.g. Piotto et al. 2004). The most popular scenarios for BSS formation in GCs are (i) direct stellar collisions between cluster members; (ii) mass transfer in and/or coalescence of primordial binary systems. Both mechanisms are likely to contribute significantly to the observed BSS populations in GCs (Davies et al. 2004), but dynamical interactions are likely to dominate BSS formation in dense cluster cores (e.g. Ferraro et al. 2004; Mapelli et al. 2004).

However, recent state-of-the-art numerical simulations suggest that even this picture is probably too simplistic. In particular, these models indicate that BSSs found in dense environments may have led much more promiscuous lives than a simple one-time collision between two single stars. Instead, many of these objects may have undergone multiple dynamical interactions involving both single and binary stars (Hurley & Shara 2002; Hurley et al. 2005).

Here, we present astrometric and photometric evidence that a previously known BSS in the core of the cluster 47 Tucanae is actually a close binary system with a BSS primary and an active lower mass secondary. If the binary is detached and the secondary is on the main sequence, this system cannot have been formed simply from a primordial binary or from just a single 2-body encounter. Its existence would therefore imply the presence of primordial triple systems in GC cores, or, more probably, the importance of more complex dynamical encounters for BSS formation. However, we cannot yet completely rule out the possibility that BSS-7 descended directly from a binary via mass transfer. A radial velocity study will be needed to distinguish clearly between these possibilities.

## 2. Observations & Analysis

The blue straggler BSS-7 in 47 Tucanae was originally discovered in ultraviolet images of the cluster core obtained with the Faint Object Camera onboard the *Hubble Space Telescope* (HST) (Paresce et al. 1991). The work on this system described here was prompted by a recently completed effort to astrometrically link a set of deep, far-ultraviolet (FUV) HST observations of 47 Tuc (Knigge et al. 2002 [hereafter K02]) with the deep X-ray images of the cluster that have been obtained with the Chandra X-ray Observatory (Grindlay et al. 2001 [hereafter G01]; Heinke et al. 2005 [hereafter H05]). In the process, we discovered a tight match between BSS-7 and the Chandra source W31, which was detected at  $L_X(0.5\text{-}6.0\text{ keV}) = 4.8^{+0.7}_{-0.5} \times 10^{30}\text{ erg s}^{-1}$  in the 2002 ultra-deep Chandra observations of 47 Tuc and which displayed X-ray variability on time scales of hours and days (H05).

### 2.1. Astrometry

Full details of our astrometric analysis will be provided in a separate publication. Briefly, the FUV imaging observations were obtained with the STIS/FUV-MAMA detector onboard HST. The F25Q7Z filter was used, giving a FUV bandpass with a mean wavelength of 1598 Å. The STIS/FUV-MAMA field of view is about  $25'' \times 25''$ , and is sampled at roughly  $0.025''\text{ pix}^{-1}$ . We have also registered a deep optical image obtained with HST onto the FUV reference frame. This image was constructed from exposures with the WFPC2/PC/F336W instrument/detector/filter combination, which provides a bandpass with mean wavelength 3367 Å. The native platescale of the WFPC2/PC data is about  $0.045''\text{ pix}^{-1}$ . For more details on the FUV and F336W images, we refer the reader to K02.

The Chandra data on 47 Tuc have been described in detail by G01 and H05. There are actually two distinct data sets, one taken with the ACIS-I detector in 2000, the other with the ACIS-S detector in 2002. The 2002 observations are considerably deeper than the 2000 ones, so we base our analysis on the 2002 data set unless specifically noted otherwise. The ACIS-S plate scale is about  $0.5''\text{ pix}^{-1}$ .

In order to astrometrically match up FUV and X-ray sources, we first applied distortion and boresight corrections to the FUV (and F336W) data. Our derivation of the boresight correction was based on 11 secure matches (taken from Edmonds et al. 2003a [hereafter E03a]) and indicates a residual transformation error between HST/STIS and Chandra positions of only  $\sigma_{trans}(\alpha) \simeq 0.009''$  and  $\sigma_{trans}(\delta) \simeq 0.040''$ . This level of precision is similar to that achieved by E03a in linking HST/WFPC2 and Chandra positions. These transformation errors were added in quadrature to the Chandra positional errors when matching up

X-ray and FUV sources.

Figure 1 shows close-ups of the FUV and F336W images centered on the Chandra source W31. BSS-7 is seen to be well within the  $3\text{-}\sigma$  error ellipse. In fact, the offset between HST and Chandra positions is only  $\Delta\alpha = 0.060''$  and  $\Delta\delta \simeq 0.010''$ , compared to the net (Chandra + transformation) error of  $\sigma_{net}(\alpha) \simeq 0.042''$  and  $\sigma_{net}(\delta) \simeq 0.064''$ . Thus the FUV source is located within  $1.44\text{-}\sigma$  of the X-ray position.

Given the radial offset of  $\Delta r = 0.061''$  between the Chandra and HST position, we can estimate the probability of a chance coincidence between an X-ray source and a BSS in our field of view. The FUV image is composed of roughly 1 million pixels and includes 19 BSSs and 40 X-ray sources. The positional offset between BSS-7 and W31 corresponds to 2.09 FUV pixels, so the probability of a chance coincidence between a BSS and a Chandra source is at most  $19 \times 40 \times 2.09^2 \times \pi \times 10^{-6} = 0.01$ . This is actually a slight overestimate, since roughly half of the X-ray sources turn out to have genuine FUV counterparts and should therefore be excluded from the random matching analysis. Thus the chance coincidence probability is less than 1%.

We note that Ferraro et al. (2001) previously suggested a possible link between W31 and BSS-7, a claim that was subsequently rejected by E03a. However, both of these analyses relied on the 2000 Chandra data set, in which W31 contributed only 7 counts (G01; H05). In the 2002 data, W31 produced 84 counts (H05), so the astrometry presented here should be considerably more secure. In particular, the alternative counterpart for W31 suggested in E03a based on the earlier data is no longer viable. We stress, however, that the different conclusions arrived at here and in E03a are mainly due to a  $0.43''$  discrepancy (corresponding to  $4.6\sigma$ ) between the position quoted in G01 for W31 (based on the 2000 Chandra data set) and the position given in H05 (based on the 2002 Chandra observations). The reanalysis of the 2000 data in H05 reduces this disagreement slightly (to  $0.32''$  or  $3.4\sigma$ ). We should finally also acknowledge the possibility that two different (variable) sources were detected and labelled W31 in the two Chandra data sets. However, for the purpose of the present study, the key result is simply the strong match between BSS-7 and W31 in the 2002 Chandra data.

## 2.2. HST Time Series

Given the apparent association between BSS-7 and W31, we decided to take a closer look at BSS-7 in the extensive HST data set described by Gilliland et al. (2000). BSS-7 is saturated in these observations, so V and I time-series photometry was extracted using the

methods of Gilliland (1994), tweaked to optimize the signal-to-noise ratio for this particular source.

The results for the I-band data are shown in Figure 2. A clear signal with  $P = 1.56$  d and amplitude  $A \simeq 0.0035$  in relative flux units (corresponding to 0.0037 mag) is clearly detected. No corresponding signal was found in the V-band light curve, but the photometric scatter in this filter was considerably larger than in I. In order to test if the non-detection of the signal in V is significant, we injected a sinusoid of similar amplitude and period as that detected in the I band into the V-band data stream. This confirmed that the V-band data is too noisy to allow detection of such a weak modulation. The I-band power spectrum also shows a peak around 97 mins, but this is probably due to instrumental effects that are modulated on HST’s orbital period (e.g. Edmonds et al. 2003b [hereafter E03b]).

### 2.3. Spectral Energy Distribution and Stellar Parameters

In order to gain additional insight into the nature of the BSS-7 system, we constructed the broad-band SED shown in Figure 3. This was achieved by extracting a set of ACS images of 47 Tuc from the HST archive, all obtained with the High Resolution Camera (HRC). These images sample the cluster core at a rate of  $0.025'' \text{ pix}^{-1}$  and were taken through a set of filters spanning the full near-UV through far-red wavelength range (F250W, F330W, F435W, F475W, F555W, F606W, F625W, F775W, F814W and F850LP). We then carried out aperture photometry on BSS-7 in all of these images, using a 6 pixel aperture radius. The resulting measurements were placed on the STMAG system by applying the appropriate aperture corrections and zero points (Sirianni et al. 2005). By deriving a complete set of magnitudes for BSS-7 from data taken with a single instrument at the highest spatial resolution, we hope to avoid the systematic errors associated with simply compiling photometry from the literature. The HST/ACS magnitudes were finally supplemented with the FUV (STIS/F25QTZ) magnitude for BSS-7 from K02. This was corrected by 0.08 mag to account for the sensitivity loss of the detector at the time of the observations (an estimate for this correction was not available at the time of K02’s publication).

We then proceeded to fit this SED with single and binary models. Our model SEDs were constructed by carrying out synthetic photometry for all our filters with the SYNPHOT package within IRAF/STSDAS. In doing so, we adopted  $d = 4510$  pc,  $[\text{Fe}/\text{H}] = -0.83$  and  $E(B-V) = 0.032$  as the relevant cluster parameters (VandenBerg 2000). In all models, the BSS spectrum was chosen from a grid of synthetic spectra spanning a wide range of effective temperatures and surface gravities. In binary models, the secondary parameters were constrained to lie on a 12 Gyr isochrone (VandenBerg 2000); this is an important constraint that

needs to be kept in mind when interpreting the results. All synthetic spectra were obtained by interpolating on the Kurucz (1993) grid of model stellar atmospheres, as implemented in SYNPHOT.

A least squares fit to the SED with a single star model yields BSS parameters of  $T_{eff}(BSS) = 7260^{+15}_{-40}$  K,  $\log g(BSS) = 3.50^{+0.15}_{-0.15}$  and  $R(BSS) = 1.73^{+0.02}_{-0.02} R_{\odot}$ . A binary model allowing for a BSS primary and a companion constrained to lie on a 12 Gyr cluster isochrone (Vandenbergh 2000) produces similar BSS parameters,  $T_{eff}(BSS) = 7300^{+50}_{-40}$  K,  $\log g(BSS) = 3.60^{+0.15}_{-0.15}$  and  $R(BSS) = 1.61^{+0.09}_{-0.11} R_{\odot}$ . However, the binary model also points to a companion on 47 Tuc’s upper main sequence, with parameters  $T_{eff}(2) = 5850^{+160}_{-930}$  K,  $\log g(2) = 4.4^{+0.2}_{-0.2}$ ,  $M(2) = 0.81^{+0.07}_{-0.15} M_{\odot}$  and  $R(2) = 0.92^{+0.26}_{-0.28} R_{\odot}$ . The addition of a binary companion reduced the scatter around the fit from 0.048 mag to 0.033 mag. According to an F-test, this improvement is significant at  $P = 0.077$ , i.e. about 92% confidence. Fig. 3 shows the best-fitting binary model superposed on the SED. The effective temperature of the BSS suggests a spectral type late A or early F, and the secondary contributes roughly 15% of the flux in the three reddest band passes.

As discussed in Section 3, the BSS surface gravity suggested by the SED fits is surprisingly low. We have therefore checked the sensitivity of the other fit parameters to the assumed gravity. For this purpose, we fixed  $\log g(BSS)$  at a value of 4.2 (based on the discussion in Section 3) and then refit the data with both single and binary models. For the single BSS model, this yielded best-fit values of  $T_{eff}(BSS) = 7200$  K and  $R(BSS) = 1.75 R_{\odot}$ . For the binary model, the best-fit parameters were  $T_{eff}(BSS) = 7380$  K,  $R(BSS) = 1.44 R_{\odot}$ ,  $T_{eff}(2) = 6000$  K,  $\log g(2) = 4.17$ ,  $M(2) = 0.87 M_{\odot}$  and  $R(2) = 1.3 R_{\odot}$ . For the purpose of our discussion below, these parameters are not substantially different to those derived from the original fit.

### 3. Discussion

In the following sections, we will first attempt to construct a consistent physical picture of the BSS-7/W31 binary system and then explore its likely formation, present state, and future evolution. However, we note from the outset that there are two possible scenarios for the formation and present state of the system, which are difficult to distinguish with the existing data. In our favoured scenario, BSS-7 is a detached binary system with an upper-main-sequence secondary, with the stellar parameters suggested by our SED model fits. This scenario implies that at least 3 progenitors are required to form the BSS-7 system. In the alternative scenario, BSS-7 would be a system that has evolved via mass transfer from a (possibly primordial) binary. In this scenario, the system is probably in a semi-detached

state at the moment, with the BSS gaining mass from a low-mass companion that has been stripped of most of its envelope. In what follows, we will first present the empirical evidence that BSS-7 consists of a BSS primary with an active companion, and then explore the two alternative scenarios outlined above.

### 3.1. BSS-7: A Blue Straggler with an Active Companion

The properties of BSS-7/W31 are unusual. In particular, we are aware of only five X-ray sources in GCs with candidate BSS counterparts; these are discussed in more detail in the Appendix. Amongst BSSs found in open clusters, four have been matched to X-ray sources (Belloni & Verbunt 1996; Belloni & Tagliaferri 1998; Belloni Verbunt & Mathieu 1998; van den Berg et al. 2004). All are thought to be binary systems. The lack of X-ray emission from single BSSs in old clusters is expected, since A- or F-type stars have at most thin convection zones and thus produce little coronal activity.

Optical variability is more common amongst BSSs in globulars, but generally falls into two clear categories. First, some BSSs are contact (W UMa) or semi-detached binaries (Rucinski 2000; A01). These systems can appear as BSSs due to mass transfer, but most such systems in GCs have orbital periods  $P \lesssim 0.5$  days.<sup>1</sup> Second, some BSSs are located in the instability strip and are therefore detected as SX Phe-type pulsational variables. However, these pulsations have even shorter periods,  $P \lesssim 0.1$  days (Gilliland et al. 1998). Clearly, the optical variability of BSS-7 does not fall into either of these categories.

On the other hand, both the period of the optical variations and the X-ray properties of W31 are typical of the active binary population in 47 Tuc (H05; A01). These systems are detached, but still relatively short-period binaries with main-sequence or sub-giant components. The high level of activity they display is thought to be linked to the relatively fast spin rate of their active components, which are usually synchronized with the binary orbit.

Thus all of the evidence we have collected is consistent with the following physical picture. BSS-7 is a 1.56-day binary system containing a BSS primary and an active secondary. The binary separation must then be  $a \simeq 7.1 \left( \frac{M_{BSS} + M_2}{2M_\odot} \right)^{1/3} R_\odot$ .

The radius of the BSS primary suggested by our SED fits is  $R(BSS) \simeq 1.6 - 1.7 R_\odot$ . This is significantly larger than the radius of a zero-age main sequence (ZAMS) star with

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<sup>1</sup>However, we note here already that there is at least one other, probably semi-detached, BSS binary with  $P \simeq 1.4$  d in a GC; this will be discussed more carefully in Section 3.2.2.

the same effective temperature ( $R_{ZAMS} \simeq 1.1R_{\odot}$ ). Thus the BSS is already slightly evolved, which is consistent with the location of BSS-7 in a FUV-F336W colour-magnitude diagram (K02).

The SED-based surface gravity estimate for the BSS is surprisingly low for both single and binary models. Taken at face value, this combination of surface gravity and stellar radius would imply an unphysically low BSS mass of  $M_{BSS} = 0.34^{+0.15}_{-0.08}M_{\odot}$  or  $M_{BSS} = 0.37^{+0.15}_{-0.10}M_{\odot}$  for single and binary models, respectively.

We can obtain an alternative mass estimate by noting that sub-giant evolution takes place at roughly constant luminosity. The mass of the BSS should therefore correspond roughly to that of a ZAMS star with the same luminosity as the BSS. This yields a more reasonable estimate of  $M_{BSS} \simeq 1.5M_{\odot}$ . We would then expect our sub-giant BSS to have a surface gravity of  $\log g(BSS) \simeq 4.2$ , considerably higher than the SED-based estimates.

Experience tells us that the systematic uncertainties on our photometric gravity estimates may well exceed their formal errors (due to uncertainties in the cluster distance, reddening and metallicity, for example). However, it is worth noting that one way to reduce the effective surface gravity of a star is via rapid rotation. This could be a direct signature of recent BSS formation in a binary merger (Rasio & Shapiro 1995) or an off-axis collision (Lombardi, Rasio & Shapiro 1996). If this is the origin of the discrepancy between expected and measured gravities for BSS-7, the BSS would have to be rotating near break-up. Taking  $M_{BSS} \simeq 1.5 M_{\odot}$  and an equatorial radius of  $R_{BSS,eq} \simeq 1.6 R_{\odot}$ , synchronous rotation with  $P = 1.56$  days corresponds to an equatorial speed of  $v_{eq} \simeq 50 \text{ km s}^{-1}$ ;  $v_{eq} \simeq 360 \text{ km s}^{-1}$  is required to produce an equatorial surface gravity of  $\log g \simeq 3.6$ . The corresponding break-up speed is  $v_{eq} \simeq 415 \text{ km s}^{-1}$ . Optical and/or infrared spectroscopy is highly desirable, both to confirm the composite nature of the SED and to check for evidence of low gravity and/or rapid rotation of the BSS.

### 3.2. The Formation, Present State and Evolution of BSS-7

#### 3.2.1. A Detached Binary with an Upper-Main-Sequence Secondary?

We now explore our favoured physical picture for BSS-7. In this picture, the binary is presently detached, and the secondary is an ordinary upper-main-sequence star. In this case, we can take our SED fit parameters as valid estimates for both binary companions.

Certainly the binary separation is large enough to accommodate both the  $1.6 R_{\odot}$  BSS and its  $0.9 R_{\odot}$  companion in a detached configuration. The observed X-ray emission and



optical variability are also consistent with this scenario. Given that the companion contributes 15% in the I-band, the observed variability amplitude of 0.35% corresponds to an intrinsic amplitude of about 2%. This is in line with the variability amplitudes of other active main-sequence binaries with similar periods in 47 Tuc (A01).

In the context of the detached binary picture, the formation of the BSS-7 binary system must have involved at least three cluster members. The only other observational evidence along these lines in the literature was based on spectroscopic mass estimates for five BSSs in NGC 6397 that exceeded twice the turn-off mass of their host clusters (Saffer et al. 2002). However, a recent reanalysis of these data shows that the spectroscopic mass estimates are subject to rather large uncertainties, and that the earlier estimates were probably biased too high (De Marco et al. 2005).

The importance of finding a BSS with 3 or more progenitors derives from the fact that the two simplest BSS formation channels – a single 2-body collision or the coalescence of a primordial binary system – cannot account for such a system. However, somewhat surprisingly, it is difficult to rule out evolution directly from a primordial hierarchical triple for BSS-7 (Iben & Tutukov 1999). In this scenario, the inner system would need to have consisted of two roughly equal-mass components with  $M \simeq 0.75M_{\odot}$  in order to produce the  $1.5 M_{\odot}$  BSS we observe today. A binary containing two such MS stars would need to be near contact to fit stably inside a 1.56-day outer orbit (Kiseleva, Eggleton & Anosova 1994). This may seem unlikely, but would be consistent with the fact that this binary then coalesced to produce the BSS. It should also be kept in mind that the presently observed 1.56-day period may have been affected by encounters with other clusters members.

However, still in the context of the detached binary picture, it seems much more likely that the BSS-7 binary system was formed directly via dynamical stellar encounters (see, for example, Hurley & Shara 2002; Hurley et al. 2005). One such route is via a single 3-or 4-body resonant interaction. During such an encounter, two (or even three) stars might have collided to form the BSS, while remaining bound to another star involved in the interaction. The biggest potential problem here is the short orbital period of the observed binary system. Numerical simulations suggest that BSS binaries produced via this channel are likely to be much wider than the binaries involved in the encounter (Davies 1995; Fregeau et al. 2004).

Another class of dynamical formation channels invokes (at least) two separate events to first form the BSS and then the binary system. Thus the BSS might have captured its companion in a dynamical encounter, such as a 2-body tidal capture or a 3-body exchange interaction. Once again, the biggest challenge (at least for an exchange encounter) is the need to account for the short period of the binary. Most exchange encounters in dynamical simulations result in binaries with much longer periods (Fregeau et al. 2004; J. Hurley,

private communication).

We finally comment briefly on the future of BSS-7 in the detached binary picture. As noted above, the BSS primary has already evolved off the MS and is currently expanding on the sub-giant branch. This must almost inevitably lead to Roche-lobe overflow. However, since the donor in this case will be more massive than the accretor, the resulting mass transfer will be dynamically or thermally unstable (depending on whether the sub-giant BSS has developed a convective envelope at the onset of mass transfer). If the mass-transfer ever becomes dynamically unstable, the system will probably enter a common envelope phase from which an even tighter binary system might emerge. However, if dynamical instability can be avoided, the mass transfer may be slow enough to allow the companion to accrete substantially from the BSS. In this case, the system may transform itself into yet another BSS binary, with primary and secondary stars exchanging roles.

### 3.2.2. *An Alternative Scenario: Semi-Detached Binary Evolution*

After this paper had already been accepted for publication, we became aware of the eclipsing, 1.4 day BSS binary NJL 5 in  $\Omega$  Cen (Niss, Jørgensen & Laustsen al. 1978). Given the similarity of the periods of NJL 5 and BSS-7, it is clearly of interest to ask what is known about the evolutionary state of the former system. Helt et al. (1993) have proposed a semi-detached model for NJL 5, in which the primary and mass gainer is a massive ( $M_1 = 1.2M_\odot$ ) BSS, and the donor is a low-mass ( $M_2 = 0.16M_\odot$ ) star. They also sketch an evolutionary scenario for this type of system, which starts with two nearly equal-mass ( $M_1 \simeq M_2 \simeq 0.8M_\odot$ ) binary components. Such a system can evolve to the present configuration of NJL 5 via mass-transfer, which is initiated when the initially more massive star (the current low-mass mass donor) first fills its Roche lobe. According to this scenario, the donor today consists of a degenerate Helium core of mass  $M_{He} \simeq 0.13M_\odot$ , covered by an extended ( $R_2 \simeq 1.27R_\odot$ ) Hydrogen layer of mass  $M_H \simeq 0.03M_\odot$ . For details on this binary evolution path, the reader is referred to Helt et al. (1993). The future of such a system will probably involve another phase of (unstable) mass transfer when the BSS expands to fill its Roche lobe.

At first sight, it may seem that we can exclude this scenario for BSS-7, since our binary model fit to the SED indicates a secondary on the upper main sequence. However, it is important to remember that our binary SED model *assumes* that the secondary is on the normal cluster isochrone. This assumption is incorrect for the low-mass secondary in the semi-detached model. In our view, an exploration of the full parameter space of the secondary ( $T_{eff}(2)$ ,  $\log g(2)$ ,  $R(2)$ ) in the SED fits is not warranted at present, since there are only 11 photometric data points which are already quite well fit by our simpler single and binary

models. Thus we cannot rule out the semi-detached model at present.

On balance, we nevertheless clearly favour the detached scenario for BSS-7, for several reasons. First, the location of BSS-7 in the cluster core makes it likely that the system should have undergone some dynamical interactions in the past (by contrast, NJL 5 is located at about 6 core radii from the center of  $\Omega$  Cen). Second, the X-ray and optical variability properties of BSS 7 are completely consistent with those of “normal” main-sequence active binaries in 47 Tuc. Third, it actually seems rather hard to avoid complete binary coalescence in the Helt et al. scenario. This is because main sequence stars become deeply convective at masses of about 0.7 and lower, and mass-transfer from such a star is thought to proceed on a dynamical timescale if the binary mass ratio is greater than 0.7. This would lead to coalescence. It is hard to see how BSS-7 could have avoided this fate during its semi-detached evolution. It is worth noting that this last comment also applies to NJL 5, and that the light curves analysed by Helt et al. (1993) actually cannot distinguish between semi-detached and detached models for this systems. However, Helt et al point out that Margon & Cannon (1989) have derived an upper limit of  $30 \text{ km s}^{-1}$  for the radial velocity of the BSS primary in NJL 5. This would suggest that the secondary in NJL 5, at least, may indeed be a low mass star.

In any case, the cleanest proof of the 3-progenitor model for BSS-7 would be to establish conclusively that the total system mass exceeds twice the cluster turn-off mass (as is indeed the case for our best-fitting binary SED model). The system parameters needed to carry out such a test should be obtainable via time-resolved spectroscopy of the system.

## 4. Conclusions

We have shown that the bright blue straggler BSS-7 in the core of 47 Tucanae is the counterpart to the Chandra X-ray source W31. We have also analysed optical light curves of BSS-7 and find a clear 1.56 day periodic signal in the I-band. We finally constructed a broad-band FUV through red SED for the system and fit this with single and binary models that take the secondary to lie on the cluster isochrone.

All of our results are consistent with the interpretation that W31/BSS-7 consists of a massive BSS primary with an active, upper-main sequence companion. If this is correct, then at least 3 progenitors are needed to form this binary system. This would rule out the simplest models for BSS formation – binary coalescence or a single physical collision – but would be consistent with N-body models in which blue stragglers often form via multiple encounters that can involve both single and binary stars.

However, even though we favour the scenario outlined above, we cannot completely rule out the possibility that BSS-7 has descended directly from a binary system via mass transfer. In this case, the secondary is a low-mass star with a Helium core that has been stripped of most of its Hydrogen envelope. Time-resolved spectroscopy is strongly encouraged in order to distinguish definitively between these scenarios.

We are grateful to Tom Maccarone for useful discussions and to Jarrod Hurley for his help in understanding the possible formation and evolution channels for BSS-7 and NJL 5. We also thank Peter Edmonds and Craig Heinke for pointing out the existence of other X-ray/BSS matches in 47 Tuc.

#### **A. Blue Stragglers in Globular Clusters with Candidate X-ray Counterparts (and some Related Sources)**

We are aware of only five X-ray sources in GCs with candidate BSS counterparts. These are W92, W163, W167 and W266 in 47 Tuc (E03; H05) and XMM source #20 in M22 (Webb et al. 2004).

W92 is the most interesting of these. It has an X-ray luminosity of  $L_X(0.5-6.0 \text{ keV}) = 2.3 \times 10^{30} \text{ erg s}^{-1}$  in the 2002 Chandra data (H05), is located at about 2 core radii from the cluster center and was identified by E03 with the 1.34-d eclipsing binary WF2-V03 discovered by A01. The astrometric match between W92 and WF2-V03 is good to  $0.07''$ , which is comparable to that between W31 and BSS-7. If the identification  $W92 = WF2-V03$  is correct, this BSS binary may be very similar to  $W31 = BSS-7$ . The fact that WF2-V03 is eclipsing would make it particularly valuable for follow-up observations aimed at measuring its system parameters.

W163 and W167 in 47 Tuc are also located outside the cluster core and have been matched to optically variable BSSs by E03 (the former match is to source WF3-V05 in A01). However, the optical periods of the counterparts in these cases are between 0.3 and 0.4 days, so they are probably W UMa binaries. These systems may appear as BSSs because of mass transfer from one binary companion to another, so there is no need to invoke three progenitors to account for these binary BSSs.

The optical counterpart suggested by H05 for W266 in 47 Tuc, source PC1-V10 from A01, is also a W UMa star (A01). However, W266 is located inside the cluster core and within the FUV field of view. In this case, our own astrometric analysis suggests that the probability of a chance coincidence is about 12 times larger than for W31, and that at least

two FUV sources lie closer to W266 than the BSS. These results will be discussed in more detail in a separate publication.

XMM-20 in M22 (Webb et al. 2004) is located just outside the half-mass radius of this cluster. The positional match between this X-ray source and the suggested optical counterpart is only good to  $4.2''$ , but given the lower spatial resolution of XMM and the relatively low stellar density in the periphery of M22, this is nevertheless a viable match with a small probability of chance coincidence.

All of these sources, but particularly W92 in 47 Tuc, deserve closer observational scrutiny to confirm the reality of the X-ray/optical matches and to determine the nature of these systems.

We finally point out 3 other BSS that have not been suggested as X-ray counterparts, but that are nevertheless particularly interesting. These are (i) PC1-V12 in 47 Tuc, which was found by A01 to be an optically variable BSS and possible active binary; (ii) V18 in NGC6397, which Kaluzny & Thompson (2003) classify as a likely detached eclipsing binary with a period of 0.8 days; (iii) V2 in Terzan 5, which was suggested by Edmonds et al. (2001) to be a likely eclipsing BSS with  $P_{orb} \simeq 14$  hrs. These sources, too, deserve closer observational scrutiny.

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Fig. 1.— Far-ultraviolet (left panel) and optical (right panel) close-ups on the vicinity of W31. The white ellipses mark the  $3\sigma$  error region around the X-ray positions in the 2002 Chandra data set. Black circles edged in white mark the location of BSS-7, our proposed counterpart for W31. Both images are roughly  $1'' \times 1''$ , with the long axes of the ellipses being oriented north-south. More specifically, north is up and to the left and east is perpendicular to this axis and down.

Fig. 2.— I-band light curve (top panel), power spectrum (middle panel) and folded light curve (bottom panel) for BSS-7 in the HST data set of Gilliland et al. (2000). A 1.56-day periodic signal is clearly visible.

Fig. 3.— The broad-band spectral energy distribution of BSS-7. All photometric measurements are plotted STMAG magnitudes at the mean wavelength of the relevant band pass. The STMAG system is defined as  $m_{STMAG} = -2.5 \log F_\lambda - 21.1$ , where  $F_\lambda$  is the flux of a flat spectrum source that would produce the observed count rate. Also shown are synthetic spectra for the best-fitting binary model (primary, secondary and combined binary). Note that the model spectra are shown as continuous curves solely for illustration; they were folded through the appropriate filter transmission curves for the purpose of fitting the SED. The bottom panel shows the residuals of the least-squares fit. The error bars shown are those needed for the best-fitting model to achieve  $\chi^2 = \nu$ , where  $\nu = N_{data} - N_{par}$  is the number of degrees of freedom. In binary model fits to the SED there are  $N_{data} = 11$  data points and  $N_{par} = 4$  free parameters (effective temperature, gravity and radius for the primary, plus the location of the secondary on the cluster isochrone).







